

**Determining Trade-off between Sustainable Yield and
Baseflow in the Kulnura – Mangrove Mountain
Aquifer System using
Simulation – Optimisation Modelling**

by

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CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

MALKHATER

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LIST OF SYMBOLS

Symbol	Description	Chapter
GWCWA	Gosford Wyong Councils' Water Authority	1
DNR	Department of Natural Resources	1, 2, 6, 8, 9
KMMA	Kulnura – Mangrove Mountain Aquifer	9
DIPNR	Department of Infrastructure, Planning and Natural Resources	2
WSP	Water Sharing Plan	2, 8, 9
f_k	filtered quickflow response at the k^{th} sampling instant	2
y_k	original streamflow at the k^{th} sampling instant	2
y_{k-1}	original streamflow at the previous sampling instant to k	2
α	filter parameter representing the degree of attenuation	2
q_k	filtered baseflow response at the k^{th} sampling instant	2
P	probability of a given flow being equalled or exceeded	2
m	rank for a discharge value	2
n	total number of streamflow readings	2
Q_t	streamflow at time t	2
Q_0	initial streamflow at the start of the recession segment	2
ΔQ	stream depletion flow rate	2
Q_w	constant flow rate abstracted at well from $t = 0$ to $t = \infty$	2
S	aquifer storage coefficient, specific yield or effective porosity	2
t	time	2, 6
l	the shortest distance between the well and stream edge	2
L	stream leakance that has a dimension of length	2

K	aquifer hydraulic conductivity	2
K'	streambed hydraulic conductivity	2
b'	thickness of semipervious layer	2
SDF	Stream Depletion Factor	2
λ	Hunt's leakage coefficient	2
M_a	number of active cells in the study area	2
a	cell index number	2
g_a	groundwater extraction by pumping in cell a	2
s_a	surface water diversion in cell a for use in cell a	2
$g_{a,k}$	groundwater extraction from cell a in time period k	2
$d_{a,k}$	streamflow diversion or reservoir release from reach e in time period k	2
M_p	total candidate number of cells from which groundwater withdrawal is optimised	2
M_d	total number of potential stream diversion reaches	2
$C_{a,k}$	coefficients to perform minimisation, maximisation or economic optimisation on groundwater extraction	2
$C_{e,k}$	coefficients to perform minimisation, maximisation or economic optimisation on streamflow diversion	2
NW	total number of wells	2
ND_k	number of days in planning period k	2
TP	total number of planning periods	2
$Q_{wi,k}$	withdrawal rate at well i during planning period k	2
$Q_{j,t}$	streamflow at reach j during time period t	2
$Q_{j,t}^*$	minimum allowed streamflow at reach j in time t	2
$Q_{sd,j,t}$	streamflow depletion at streamflow constraint site j in month t	2
$(Q_{sd,j,t})_{\max}$	maximum rate of streamflow depletion allowed at site j in month t	2

	in month t	
$Qsd_{j,t}^*$	streamflow depletion at site j in month t in response to a unit withdrawal Qw_i at well i	2
$r_{j,i,t}$	response coefficients for each well and streamflow constraint site pair	2
$Qw_{i,t1}$ and $Qw_{i,t2}$	withdrawal rates at well i in month t1 and t2	2
$\alpha_{1,2}$	ratio of total demand in month t1 to total demand in month t2	2
$S(k,n)$	drawdown at site k at the end on nth period	2
$\beta(k,j,n-i+1)$	response coefficients	2
$q(j,i)$	pulse pumping at site j and time i	2
M	total number of wells	2
n	total number of planning periods	2
k	observation site location	2
RM	Residual rainfall mass	4
$RAIN_{month}$	Total monthly rainfall in month A	4
\overline{RAIN}_{month}	Mean monthly rainfall for month A in all years	4
®	Automatic Water Level Recorder	4
AMG	Australian Map Grid	4
AHD	Australian Height Datum \approx Mean Sea Level	4
K_x, K_y, K_z	values of hydraulic conductivity along the x, y and z coordinate axes	6
K_{rw}	relative permeability, which is a function of water saturation	6
h	hydraulic head	6
W	volumetric flux per unit volume and represents sources and/or sinks of water per unit of time	6

S_w	degree of saturation of water, which is a function of the pressure head	6
S_s	specific storage of the porous material	6
S_y	specific yield	6
Q	flux into boundary cell	6
H_b	boundary head	6
H_m	head computed by model	6
C	boundary conductance	6
K_b	hydraulic conductivity of the boundary material	6
A	area of the boundary	6
B	thickness or width of boundary	6
SQR	Sum of Squares Residual	6
W_i	dimensionless weighting fraction (ranges from 0 to 1) for each i measurement in n samplings of data	6
h_i	modelled head	6
H_i	measured head	6
R_i	Residual	6
SR	Sum of Residuals	6
MSR	Mean Sum of Residuals	6
SMSR	Scaled Mean Sum of Residuals	6
SSQ	Sum of Squares Residual	6
MSSQ	Mean Sum of Squares	6
RMS	Root Mean Square	6
RMRS	Root Mean Fraction Square	6
SRMFS	Scaled Root Mean Fraction Square	6
SRMS	Scaled Root Mean Square	6
CD	Coefficient of Determination	6

w	total number of bores	8
p	total number of planning periods $p \geq 1$	8
$Q_{k,t}$	total amount of groundwater withdrawal at bore k and planning period t	8
$DD(i,j)$	Maximum allowed drawdown during pumping	8, A
$H_{OS}(i,j)$	Natural pre-pumping head at the observation site i,j	8
$H_{DB}(i,j)$	Head at the drain (stream) boundary i,j	8, A
T	hydraulic gradient reduction tolerance fraction	8, A
GAMS	General Algebraic Modelling System	8
SDF	Stock-Domestic-Farming bores	8
$H_{N(i,j)}$	Natural pre-pumping head at the observation site i,j	A
$H_{S(i,j)}$	Stressed during-pumping head at the observation site i,j	A
x	Distance between the observation site and the drain boundary	A
$\Delta H_{N(i,j)}$	Head difference between the observation site i,j at pre-pumping condition and the drain boundary i,j	A
$\Delta H_{S(i,j)}$	Head difference between the observation site i,j during pumping and the drain boundary i,j	A

ABSTRACT

The public water supply in the Gosford-Wyong area of New South Wales is reliant on streams that originate in elevated sandstone country. About half of the stream flow is believed to be baseflow from the sandstone aquifer system in the Kulnura - Mangrove Mountain area. At the same time as the population is growing steadily on the coast, there is increased demand for groundwater for horticultural, agricultural and industrial purposes along the sandstone ridges. Hence, good groundwater management is critical, to ensure that stream baseflow is not jeopardised.

A management model that couples a simulation model with an optimisation model has been developed for the Kulnura-Mangrove Mountain aquifer system to evaluate the trade-offs between increased aquifer yields and baseflow reduction. The project has been successful in developing trade-off curves for sustainable yield versus reduction in baseflow. It is believed that this is the first time that rigorous trade-off curves for sustainable yield have been developed for a stream-aquifer system in Australia.

The objectives of this research were to determine the sustainable yield(s) of the aquifer system in relation to extraction limits from both groundwater and surface water; to determine the magnitude, distribution and dynamics of baseflow to the streams which drain the Kulnura – Mangrove Mountain aquifer; to determine groundwater entitlement limits that would preserve baseflow to streams in order to facilitate groundwater allocation policy; and to explore how groundwater extraction limits would change for tolerable reductions in baseflow.

The simulation model is necessarily coarse, with 500 m spatial resolution, as replication of a very large regional aquifer was required. Given the wide variation in vertical relief in the area, approximately 400 metres, it was necessary to divide the vertical profile into 30 layers. Otherwise, it would not have been possible to track the many baseflow-receiving creeks that descend from high elevations to the sea.

The calibration results of the simulation model show that the model performs very well in representing the values and the patterns of groundwater level for both steady state and transient conditions, is able to reproduce large vertical hydraulic gradients between aquifer layers, and also replicates baseflow reasonably well.

The optimisation model was developed with the objective of preserving stream baseflow within tolerable limits while maximising the pumping rates from the aquifer system. Constraints were designed in terms of hydraulic gradient, with reduction tolerance ranges from 0.1 % to 10 %. Conversion from hydraulic gradient reduction to baseflow reduction was achieved by running reported optimal production patterns through the model in simulation mode. This work differs from that of previous researchers in not making a pre-emptive assumption of linearity between groundwater pumping and stream baseflow.

A very large optimisation problem has been solved in this study, consisting of up to 5700 decision variables and 8000 constraints. The study has been successful in generating trade-off curves that will provide a scientific basis for government / community decisions on responsible water allocation between computing users.